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Achieving load relief with minimal change in conventional control law of a launch vehicle

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Abstract: This article is about managing the structural load due to winds on a launch vehicle during its atmospheric flight. Wind generates aerodynamic force on the vehicle. The other sources of force on the vehicle are thrust and weight. These forces generate moment on different structural members of a launch vehicle, depending on their point of application with respect to the location of a particular structural member. Together these forces and moments generate tension, compression, shear and bending loads at different locations on the launch vehicle. If the in-flight loading exceeds the structural limit of any member, the vehicle would break. In this paper we have explored the possibility of achieving load relief without using any additional sensor or scheduling of any additional gain. This methodology is useful if the requirement for achieving load relief comes very near to the launch date. In this scenario, the control designer will not have enough freedom to go for wholesale changes in the already existing onboard software of a prevailing conventional control law. This restriction is due to the necessary time required for verification and validation of modifications in code.

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Keywords: estimator, attitude control, load relief, pole assignment

1. INTRODUCTION

Structures with high length to diameter ratio, like launch vehicle, have high flexibility. They are prone to break when subjected to excessive load. Any structural member of a launch vehicle is subjected to mainly three kinds of loads i.e. axial load (tensile and compressive), shear load and bending load. Tensile and compressive loads are due to mainly thrust and inertia forces. The other two types of loads i.e. sheer and bending load are mainly due to aerodynamic force and moment. Wind generated aerodynamic load on any launch vehicle depends on three parameters. They are dynamic pressure, angle of attack and aerodynamic force and moment coefficients. Out of these three factors, dynamic pressure depends on the trajectory to be followed by the launch vehicle. Aerodynamic force and moment coefficients depend on the aerodynamic configuration of the launch vehicle. The third component i.e. angle of attack is the angle between the longitudinal axis of the vehicle and the relative velocity vector. Angle of attack on launch vehicle depends on the wind profile faced by the vehicle during the flight. It also depends on the response of the launch vehicle flight control system to the wind disturbance. Load relief methods generally try to reduce this angle of attack thereby reducing the aerodynamic force and moment on the vehicle. Reduced force and moment generate low structural load on the vehicle.

Load relief is not a new concept. Early paper by Livingston et. al. (1968) discusses the difficulties designers face while modifying an existing control law to bring in the load relief feature in it. Scenarios when this kind of need comes, various options available with launch vehicle engineers and different possible modifications of control law to provide load relief are all covered in the paper. In the special section of Baruh et. al. (2000), launch vehicle atmospheric flight load analysis is discussed. Load relief autopilot design based on lateral acceleration sensing is detailed in Kurt et. al. (1991). Another paper where body acceleration measurement based load relief scheme is discussed is Jiann et. al. (2011). Concept of active load relief based on angle of attack estimation is discussed in Bonnice et. al. (1983). Use of model predictive control, with Light Detection and Ranging (LIDAR) sensor for wind measurement, in reducing aerodynamic load on the launch vehicle is discussed in Andrew et. al. (2002). Estimation of angle of attack (AOA) and then the reduction of AOA when it exceeds the limit values of AOA, is discussed in Frederic et. al. (1989). In Matthew et. al. (1992), AOA estimate is used to keep the total AOA on the vehicle within a limit.

The focus of present paper is to simplify the AOA estimator based add-on load relief module such that with bare minimum change in conventional control law, load relief provision can be implemented. Since the changes are minimum, there is no need to change the existing on-board code of prevailing conventional control law. This saves a lot of time, otherwise required for verification and validation of any new on-board code and makes the change acceptable for an imminent flight. Lateral acceleration feedback based control law design for load relief is not considered in the paper as it requires wholesale change in the existing conventional control law of a launch vehicle.

Rest of the paper is arranged as follows. Section 2 describes the plant modelling with different variables used for feedback. Section three covers the details of conventional

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launch vehicle attitude control law. Additional modification in control law to bring-in load relief feature is also detailed in this section. Considering a numerical example given in Najiya et. al. (2015), design details of load relief control law and simplified load relief control law are given in section 4. Time domain and frequency domain results in terms of command tracking, robustness and disturbance rejection are also compared in the same section. The paper is concluded in section 5.

2. PLANT MODELLING

Unlike aircraft, launch vehicle attitude dynamics is fairly decoupled in pitch, yaw and roll channels. During atmospheric flight, where there is a requirement to keep the structural load on the launch vehicle within limits, rigid body attitude dynamics in pitch and yaw are modelled as a third order dynamics. This model considers short period rotational dynamics due to moment, and drift dynamics due to side force. Force along the longitudinal axis is not modelled as for the short span of time longitudinal velocity is assumed constant.

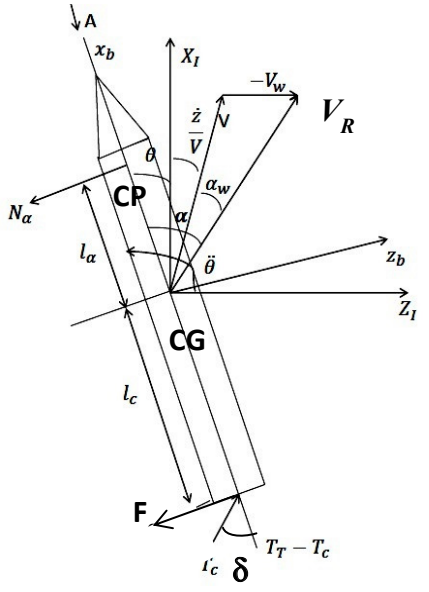

Fig. 1. Aerodynamic configuration and sensor location of a reusable launch vehicle

Figure 1 depicts all the forces and moments acting on the vehicle in the pitch plane. Pitch axis is perpendicular to the plane of the paper and it points outward towards the reader. Whenever there is non-zero angle (AOA) between the vehicles longitudinal axis (X) and relative velocity vector V_R, there will be lateral force N_α acting on the vehicle. Since this force acts at a point on the longitudinal axis known as centre of pressure (CP), which is mostly situated ahead of centre of gravity (CG) of the vehicle, there will be an aerodynamic moment around CG, which further increases the AOA. This in-turn further increases the aerodynamic disturbance force and moment. Finally vehicle tumbles as the CP ahead of CG is an aerodynamically unstable configuration for any launch vehicle. Invariably launch vehicles are aerodynamically unstable as most of the mass is concentrated in the lower stages of the launch vehicle. Large fins are required to be attached to the lower stages of the vehicle to bring the CP below CG. This is not feasible due to other practical (payload optimization) and physical constraints.

To stabilize any launch vehicle, control moment M_c is required to oppose the aerodynamic disturbance moment. This moment is normally generated by deflecting the thrust vector using gimbaling of the nozzles. By gimbaling the nozzle side force $F_c = T_c.sin(\delta)$ is generated, which in turn generates $M_c = F_c * l_c$ at CG. Here δ is nozzle rotation, l_c is distance between nozzle gimbal point and CG and l_α is the distance between CP and CG (Fig. 1).

Since the launch vehicle is an inherently flexible structure, the attitude and attitude rate sensors mounted on the vehicle, measure flexible vibrations also along with the rigid body rotation and rotation rates. Similarly the commands generated by autopilot, to deflect nozzle, gets modified by the rotational component of vibrations at the gimbal point. It means that the sensed parameters to be used by autopilot and the commands generate by autopilot both get modified by flexibility of the vehicle. Complex vibrational motion of the vehicle is decomposed in terms of pure sinusoidal components at different frequencies. These sinusoidal components of actual vibration of the vehicle at different frequencies are known as bending modes (BM). These modes are numbered as first bending mode (BM1), second bending mode (BM2) and so on. Bending modes at lower frequencies are of more importance as the actual deflection of vehicle mainly consists of these low frequency modes. Modes corresponding to higher frequencies do not participate much in vibration as vehicle structure does not respond to high frequencies. Generally first three bending modes are considered for compensator design in control law. Among these three, first mode is phase stabilized, i.e. through autopilot, damping of this mode is enhanced. Second and third modes of importance are notched out (gain stabilized) to avoid any possibility of enhancing these bending modes through nozzle deflection by autopilot. By suppressing these bending modes in control law, control structure interaction is avoided.

Detailed modelling of launch vehicle attitude dynamics is given in Greensite (1970) and Jeb et. al. (2009). Considering one flexible mode along with rigid body dynamics, linear plant model has five states. They are body attitude- θ, attitude rate - q, AOA related to side drift - $\dot{z}/V$, generalized coordinate - q_1 w.r.t. BM1 and its rate - $\dot{q}_1$. Plant model has two inputs i.e. nozzle deflection δ and wind disturbance in terms of wind induced AOA α_w. There are three outputs i.e. θ, q, and α out of which AOA is not measurable as AOA sensor is not available. Numerical values for linear plant model in state-space form, considering rigid body and one flexible mode dynamics, as given in Najiya et. al. (2015).

Along with linear plant model, control law designer needs to consider the lags added by on-board computer, actuator and various sensors. Though actuator dynamics is non-linear and its response depends on command amplitude, for atmospheric flight where commands are near 5%-10% of full scale

deflection of actuator, actuator dynamics can be represented by a linear second order model with 5 Hz bandwidth and 0.5 damping cascaded with a first order lag at 9.55 Hz. Similarly, delay added by sensors and on-board computer is represented by a lumped third order dynamics having second order leg with 5.5 Hz, 0.6 damping and first order leg at 9.55 Hz. Both the approximate models of actuator and sensor-delay have unity gain at steady state.

The (2,3) element of the state transition matrix represents an important coefficient known as aerodynamic disturbance moment coefficient (μ_α), which is nothing but the aerodynamic disturbance rotational acceleration (deg/s^2) generated by one degree increase in AOA. It is an indicator of aerodynamic instability. Minimum closed-loop BW required for feasibility of closed-loop control (Gopal et. al. (2012)) depends on it. It is shown in Gopal et. al. (2012) that the closed-loop bandwidth should be more than $2\sqrt{(\mu_\alpha)}$. This value is at-least 0.9 Hz for the numerical model considered in present study. Now to reduce lag added by actuator, its BW should be at least four times of this value. This boils down to the need to having actuator band width (BW) more than 3.6 Hz. This requirement is met by the actuator considered for the present design.

3. CONVENTIONAL AND LOAD RELIEF CONTROL LAW

Control law for attitude dynamics is required to stabilize the unstable short period attitude dynamics of an aerodynamically unstable launch vehicle. For this purpose attitude and attitude rate feedback signals are obtained using attitude gyro placed near vehicle nose and rate gyro placed near the middle portion of the vehicle length. Placement of sensor in this way helps in stabilization of vehicle flexibility. Conventional control law block diagram is given in Fig. 2. Since commanded attitude rate is low for launch vehicles, generally commanded rate is not subtracted from the sensed rate, as shown in Fig. 2. In Fig. 2, ACT is actuator-sensor-delay model, K_A is forward path gain, K_R is rate path gain, APF is attitude error path filter, RPF is rate path filter and FPF is forward path filter.

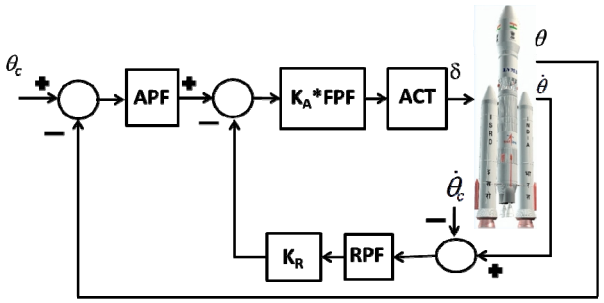

Fig. 2. Conventional control law block diagram

With these two gains, it is possible to modify only two poles related to short period dynamics to overcome aero instability.

In linear plant model there is a pole-zero pair corresponding to lateral force dynamics. It is not possible to directly influence this drift-pole dynamics. For vehicles with higher aerodynamic normal force, this pole-zero pair is well separated and they don't cancel each other's effect. This leads to presence of a pole very near to origin, leading to large steady state error and sluggish first order dominant response of closed-loop attitude dynamics. To influence this dynamics one needs an additional feedback using AOA. Since launch vehicles travel at supersonic and hypersonic Mach numbers, conventional AOA sensors used in aircraft attitude control could not be used. An alternate to AOA sensor is lateral acceleration sensor. The problem with this alternative is that acceleration sensor measures gravity and control force also along with aerodynamic force, which is of more interest to the designers. Since our aim is to provide load relief without the use of any additional sensor, acceleration measurement based control law design is not considered in the present study. Interested readers can refer to (Najiya et. al. (2015)) for details on load relief control law based on acceleration measurement.

Since the sensor for measuring AOA is not available, we need to estimate AOA from the available measurements of attitude and attitude rate. If we consider only the third order rigid body dynamics as done in Najiya et. al. (2015) then we only need to estimate one out of the three states as the other two states are already available in measurement. With this, AOA estimator dynamics reduces to first order dynamics. In the present paper load alleviation is done via AOA estimation and its control. Estimator based control law is depicted in Fig. 3.

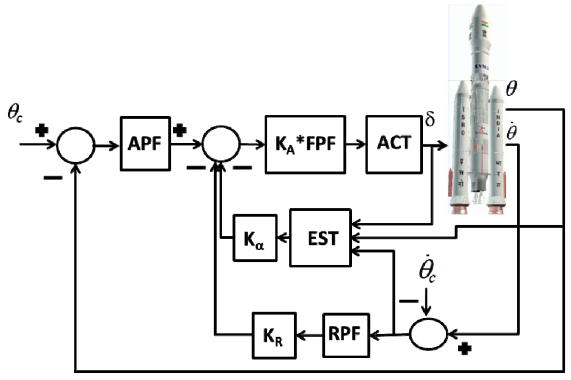

Fig. 3. Estimator based Control law block diagram

With respect to conventional control law, there are two additional parameters K_α (AOA feedback gain) and EST (estimator) in Fig. 3. Since the launch vehicle plant is linear time varying, these additional components need to be scheduled w.r.t. time. To avoid gain scheduling and estimator scheduling, in the present study, these two components of control law are computed at peak criticality Mach number during the flight. With fixed values of estimator and AOA feedback gain, before and after this critical Mach number, closed-loop system is evaluated in terms of command tracking, robustness and disturbance rejection capability. This is the first proposed simplification of add-on load relief module.

Invariable K_α and estimator parameters are sufficient as they ensure load minimization at peak load point. On both sides of peak load Mach number, conditions from load point are

naturally benign due to the bell shape dynamic pressure profile, the launch vehicles generally face during the atmospheric flight. In Fig. 4 a typical Mach No. and dynamic pressure profile is shown. The design of load relief add-on module is done at 50 sec and used from 30 sec till 80 sec.

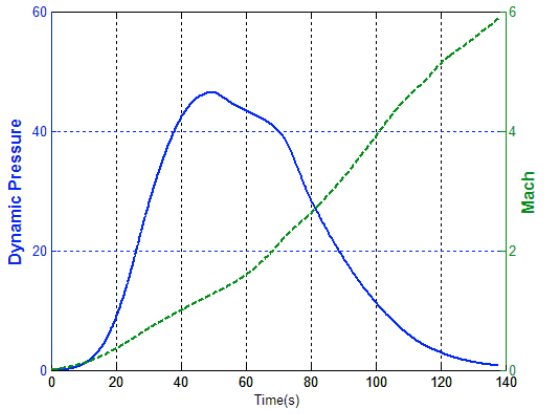

Fig. 4. Typical flight Mach and dynamic pressure profiles

To further simplify, attitude and nozzle deflection command dependency of estimator is removed by making corresponding gains in estimator, zero. Now the AOA estimate has only one input i.e. attitude rate. With this simplification there remains two parallel paths, one with K_R and RPF and another with K_α and EST, between attitude rate and summer existing before the forward path gain K_A. Using block diagram reduction methodology, these two parallel paths are combined to a single path with K_R*LRF. LRF is load relief filter, which depends on rate path filter (RPF), simplified estimator (EST), K_R and K_α. LRF = RPF.$\{1 + (K_\alpha/K_R).\alpha/q\}$. This simplification made it possible to use the on-board control law code written and tested for conventional control law (Fig. 2) and provide load relief feature, just by replacing coefficient values of RPF by that of LRF.

With this highly simplified scheme of load relief, use of command rate in control law becomes very important. Control law should essentially operate on rate error feedback and not on rate itself, as is done generally for conventional control law of any launch vehicle. The need for removing the commanded rate from the sensed rate before passing it to load relief filter is described in Fig. 5.

Active load relief requires modification of nozzle deflection in real time in proportion to the change in AOA. For launch vehicles with lower value of (μ_α), there is no provision of active load relief. However, attitude command is biased corresponding to a measured wind profile (Sivan et. al. (2007) and Gale et. al. (1971)) such that total angle of attack on the vehicle is reduced to zero. Wind measurement is done using balloons, very near to launch time. It is assumed in this scheme that the wind profile does not change much from the measured wind before the launch.

Vehicles attitude changes in response to the commanded rate due to wind biasing, residual wind AOA which could not be compensated by passive load relief and force generated due to the residual AOA remaining due to attitude error in following the command. Only the rate related to total residual AOA need to be passed to the estimator, otherwise this scheme will even work against passive load relief scheme itself. Component of attitude rate corresponding to commanded attitude rate need to be removed as with this attitude rate, estimator will estimate back the AOA which is already compensated by wind biasing of the attitude command. Control law will generate a command which will oppose rotation of vehicle in response to attitude command. In the next section, details of control law design using actual AOA and estimated angle of attack are discussed.

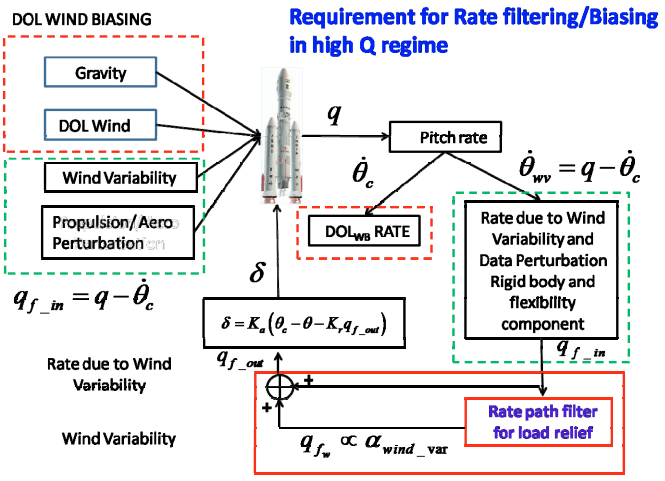

Fig. 5. Simplified active load relief scheme

4. COMPARISON OF ACTUAL LOAD RELIEF CONTROL WITH TUNED LOAD RELIEF CONTROL

In the beginning it is assumed that the AOA is also available as measured input along with pitch attitude and attitude rate. Though the plant dynamic is actually fifth order dynamics, (leaving sixth order hardware dynamics representing actuator, sensor and on-board computation delay) for finding out the feedback gains only third order rigid body dynamics is considered. Since all the three states are assumed measureable, full state feedback gains are computed for desired location of close loop poles. In the linear dynamics considered, there are two poles related to short period dynamics and one pole related to drift-pole dynamics. Desired pole locations are modified to maximize stability margins and to improve wind disturbance rejection. This led to the selection of two poles at 1.98 r/s and 1.5 damping and one pole at -0.8 locations. With these specifications for desired closed-loop pole locations, computed rigid body feedback gains are K_A = 3.168, K_R = 1.3164 and K_α = -0.0944. An integrator gain K_i of 0.25 is considered to remove the tracking error.

Once flexibility dynamics is introduced, there is significant amount of loss in gain margin. To regain back the gain margin, lag-lead compensator is designed. With this, the finally achieved margins are shown in Fig. 6. Full state feedback gains, thus designed, ensured gain margin (GM) of 4.7 dB, gain reduction margins (AM) of 3.7 dB, rigid body phase margin of 19.9 deg. Flexible dynamics lead-phase-margin of 55.7 deg and corresponding lag-phase-margin of 114 deg. Response of closed-loop system to step attitude

command is given in Fig. 7. More than 100% of peak overshoot is seen. Significant amount of build-up in AOA, pitch rate and nozzle deflection command is also seen in the time domain responses. Response to synthesized wind AOA is given in Fig. 8. There is marginal build-up of AOA to sheer and gust. At steady state, vehicle drifts along with the wind to nullify the wind generated AOA. There is no attitude error at steady state. To assess the wind disturbance rejection property in frequency domain, bode plot of α/α_w is given in Fig. 9. Wind disturbance rejection is least at 2 r/s. In reality, it is an amplification of α_w by 7.87 dB at this frequency. However steady state wind AOA is well attenuated.

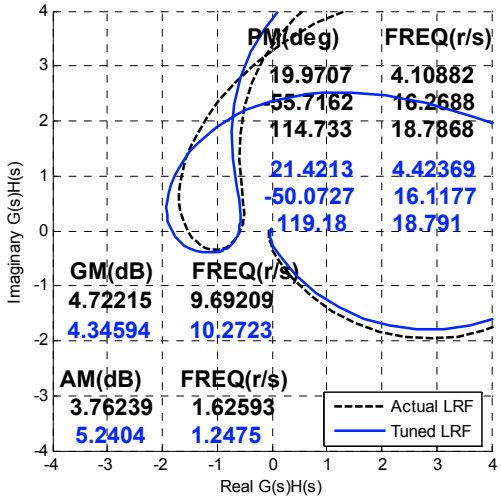

Fig. 6. Stability margins comparison for load relief schemes

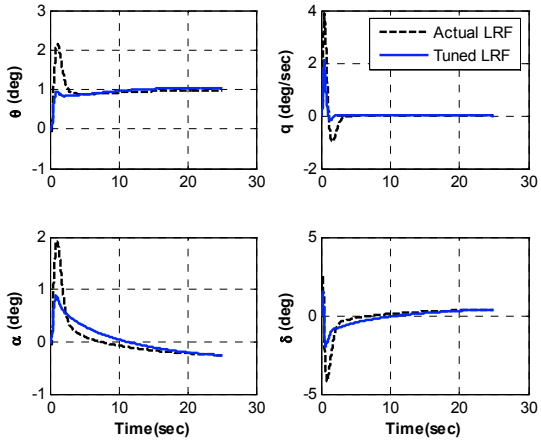

Fig. 7. Step response comparison for load relief schemes

To estimate the AOA from the attitude rate, α/q transfer function is derived from third order plant dynamics by dividing α/δ transfer function by q/δ transfer function. Bode plot of this transfer function is shown in Fig. 10. If we cancel pole at origin with zero at -0.0471 as they are very near, the remaining α/q transfer function is represented as approx α/q transfer function in Fig. 10. This approximate transfer function has constant gain at DC frequency. Now to construct load relief filter (LRF) from this α/q we have used the relationship LRF = RPF.$\{1 + (K_\alpha / K_R).\alpha/q\}$ as described in Section 3. Plot of this transfer function is also given in Fig. 10. This transfer function has unity gain at infinite frequency.

The responses given in Figs. 6-9 do not change if we use this LRF in rate path in place of alpha feedback.

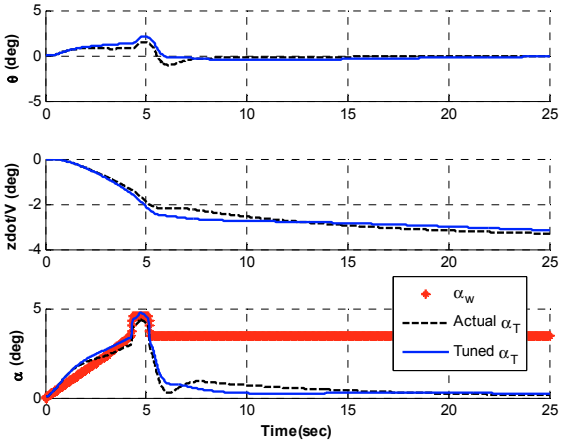

Fig. 8. Disturbance rejection comparison

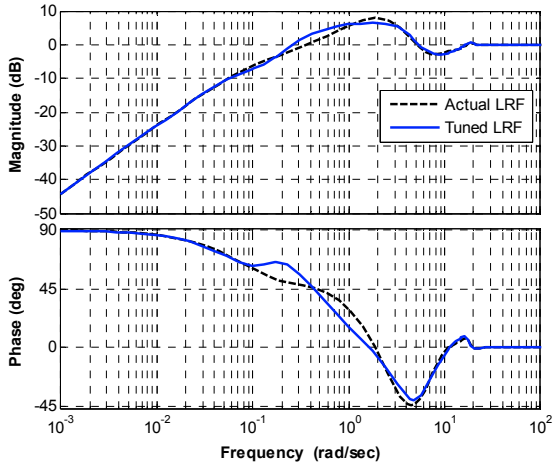

Fig. 9. Disturbance rejection comparison bode plot of α/α_w

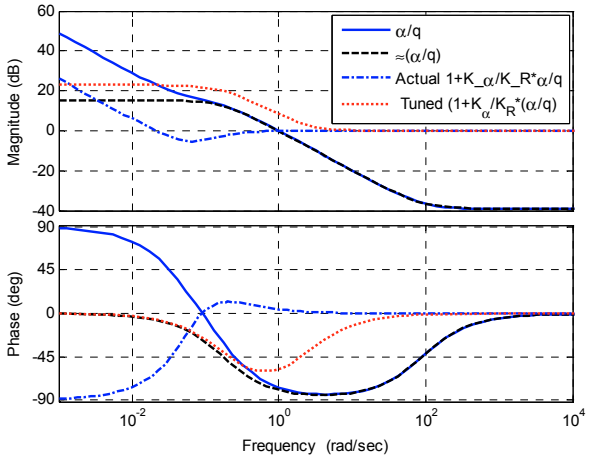

Fig. 10. Comparison of α/q and load relief filters

Our contribution is in treating LRF as another compensator which can be tuned to improve frequency and time domain responses of closed-loop system. In place of using LRF as it is, a tuned load relief filter is designed as a first order gain boosted lag which has fixed DC gain and unity infinity gain. This tuned LRF is shown in Fig. 10. All the other

components of control law are also re-tuned. There was improvement from all the sides except lead phase margin at BM1 frequency. To improve it, a notch filter, which essentially adds lag at BM1 frequency and suppresses other higher bending modes, is introduced. With all these changes, the final margins are given in Fig. 6. Second entries off all the margins are corresponding to tuned LRF. Modified control law ensured 4.3 dB gain margin which is slightly lesser than the one achieved with AOA feedback. AM has significantly improved. It has changed from 3.76 dB to 5.24 dB. Phase margin has also improved by 1.5 deg. BM1 lead margin is 50 deg. There is 5 deg reduction but lead margin is still more than the design specification of 40 deg. Lag margin is already very high in both the cases. The main advantage is seen in step response where peak overshoot has reduced from 100% to 10% as compared in Fig. 7. Minor increase in AOA build-up in response to sheer and gust is of the order of 0.5 deg as seen in wind disturbance rejection plot (Fig. 8). In frequency domain comparison plot of $\alpha/\alpha w$. there is reduction in peak wind response from 7.87 dB to 6.47 dB with tuned LRF filter (Fig. 9).

In nutshell, the proposed scheme has improved robustness, tracking performance and disturbance rejection property of the closed-loop system. Load relief is achieved, with only change in numerical values of the coefficients to be used in control law. This is the simplest solution of achieving load relief from the flight software written for conventional control law.

5. CONCLUSIONS

This paper describes a simplified reduced order observer based active load relief scheme. The scheme discussed in the paper is very useful, especially if very close to the launch date, the control designers are asked to reduce the in-flight load on the vehicle. There are many reasons for such scenario to arise. One such reason is some urgency to launch in a rough weather. The contribution of authors is in simplification of the load relief scheme such that it can be implemented without any code modification in the already existing on-board flight control software. The coefficients of the rate path filter need to be modified to bring in the feature of load relief. Along with this, the other parameters of control law need to be modified suitably for load relief control law. Proposed modification in control law requires only the change in numerical values of control parameters in flight software, however flight software code remains unmodified.

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